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Envelope of Correlation Used with Deconvolution and Reconvolution to Remove the Direct Arrival in a Multipath Environment

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ABSTRACT

Separating overlapping direct and reflected arrivals, such as those propagated under pack ice from an acoustic source emitting frequency modulated sweep pulses, is a difficult problem in the analysis of high frequency arctic data. To solve this problem, a correlation with the source pulse followed by a Hilbert transform is used to derive the envelope of correlation. This gives a reliable indication of the best cutoff time for separating multipath arrivals by a deconvolution followed by reconvolution. An added benefit from the software for the above cross correlation envelope is a plot of the relative amplitudes and arrival times for each propagation path.

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INTRODUCTION

Under pack ice in deep arctic waters, high frequency acoustic signals are often received by direct and reflected paths at close to the same time. These arrivals interfere with each other when they overlap. This is shown in Figure 1, which is typical of frequency modulated (FM) data from two propagation experiments designed to study spatial coherence under pack ice[1]. In these experiments, conducted using similar equipment in 1986 and 1987, 100 millisecond acoustic linear FM sweep pulses, like that shown in Figure 2, were transmitted from source locations 61 and 91 m deep. The pulses had 800 Hz bandwidths centered at frequencies from 11 to 59 kHz. They were received at

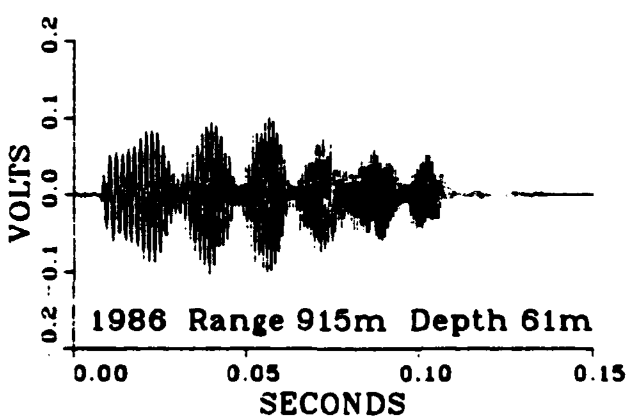


Figure 1. Total received signal at channel 7 of the 16 channel array, 1986 experiment, with a source depth of 61 m. Shows interference between the direct and reflected arrivals.

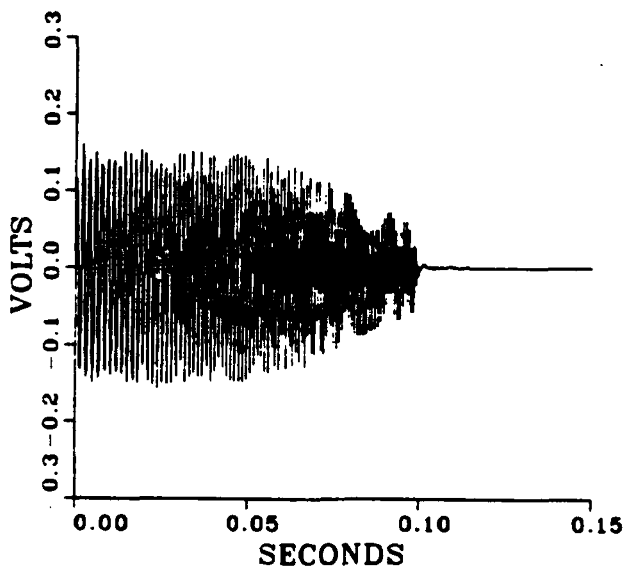
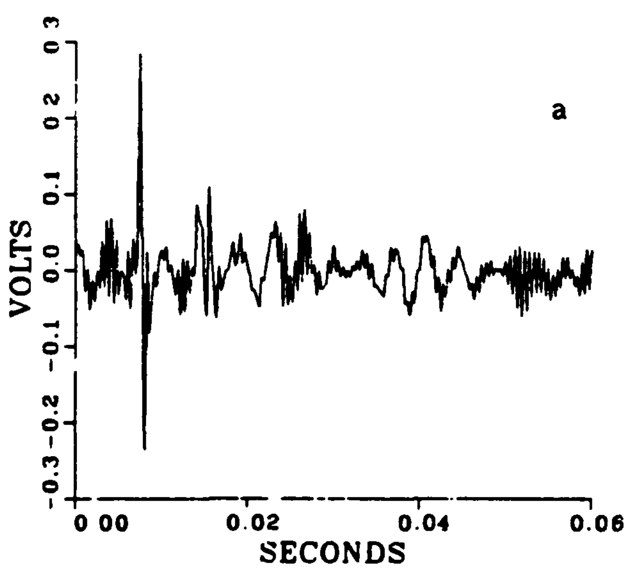
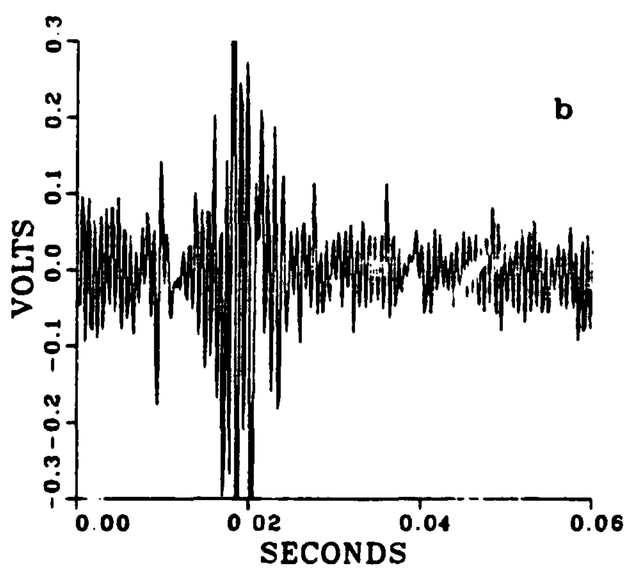


Figure 2. Source pulse for 1986 data.

normal incidence by a sixteen channel horizontal array at a depth of 61 m. The array was 16 meters long with hydrophones spaced according to a suboptimal minimum redundancy algorithm at .2, .4, .6, .8, 1.0, 1.2, 1.4, 3.3, 5.1, 7.0, 8.8, 10.7, 12.5, 14.4, and 16.0 m from the first hydrophone. Received signals were heterodyned down to a 900 Hz center frequency. The horizontal range between source anc' array was 915 m in 1986 and 968 m in 1987.



1986 Range 915m Depth 61m



1987 Range 968m Depth 91m

Figure 3. Deconvolution of data with source pulse.

DATA ANALYSIS

History of Separation Techniques

In order to determine the spatial correlation of the ice-reflected arrival, it is necessary to remove the overlapping direct arrival from the total received signal. Procedures for separating multiple arrivals have been devised by combining acoustic data processing methods with those used by geophysicists in studying seismic data. Berkhout summarized acoustical echo techniques and the properties of different types of deconvolution, also referred to as inversion or filtering, used to increase the resolution of seismic data arrivals[2]. Dicus used a deconvolution to remove bubble pulses from underwater explosive source, direct-path acoustic signals[3]. In adapting these techniques to separating the FM slide arrivals in the Naval Oceanographic and Atmospheric Research Laboratory (NOARL) high-frequency arctic correlation studies, priority was given to developing quick, streamlined computer software and obtaining reliable results from real experimental data.

Method of Separation

The first step in removing a direct arrival from the received signal uses a source pulse, like the one in Figure 2, to deconvolve each hydrophone output and obtain pulse amplitude as a function of time. If the direct signal is a replica of the source pulse with only a time delay and an amplitude change, it will show up in the deconvolution as a spike. Deconvolution of the pulse in Figure 1 with the pilot trace in Figure 2 is shown in Figure 3a. Ideally, this spike can then be removed from the deconvolution and a reconvolution performed to obtain a time history of pressure due to other arrivals. In practice, as shown in Figure 3b, a clean spike is seldom found. Therefore, nulling of the deconvolution over a finite extent is required. To accomplish this, we select a time between the direct arrival peak and the reflected arrival peak and set the deconvolution to zero before that time. Reflected signals obtained using three different selections of cutoff time are shown in Figures 4 a, c, and e. The complementary direct signals, obtained by subtracting the reflected time series from the total signal, are shown in Figures 4 b,d, and f. Spatial correlation calculations for the reflected signals cannot be obtained unless the correct separation of arrivals is achieved.

Determining the Cutoff Time

Several algorithms for determining relative arrival times of direct and reflected parts of an overlapping total signal have been tried. First, the cutoff time was automatically selected halfway between the two largest spikes in a deconvolved signal. This works well for the ideal case and some of the real data. The example from the 1986 data, Figure 3a, would yield the correct result

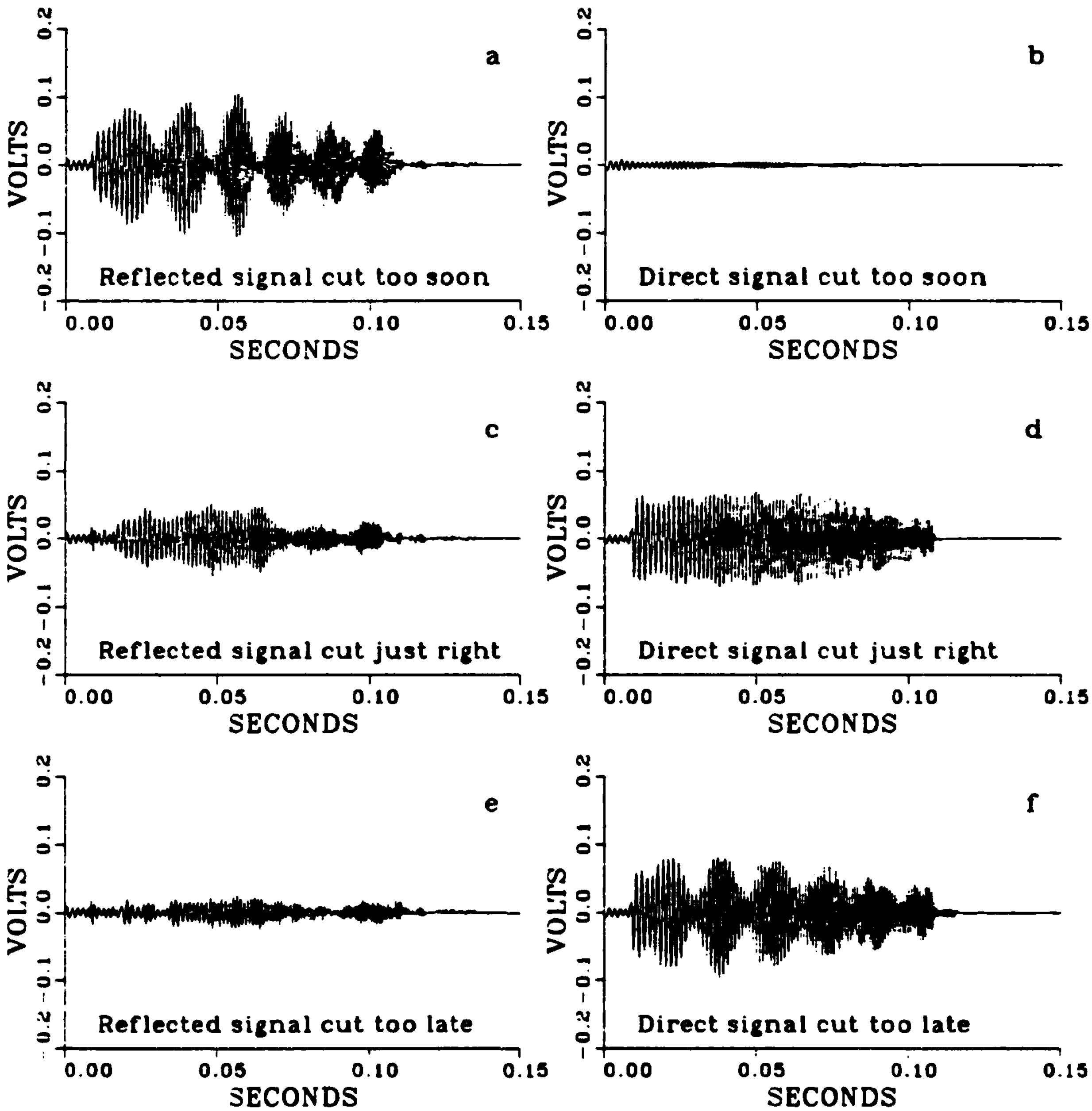


Figure 4. Data used was from the 1986 experiment with 61 m source depth. Reflected signals obtained by reconvolution of the deconvolution time series after all its points before the cutoff time were set to zero. Direct signals are the total signal minus the reflected signal. In a and b the cutoff time was .005 seconds, in c and d, .010 seconds, and in e and f, .017 seconds.

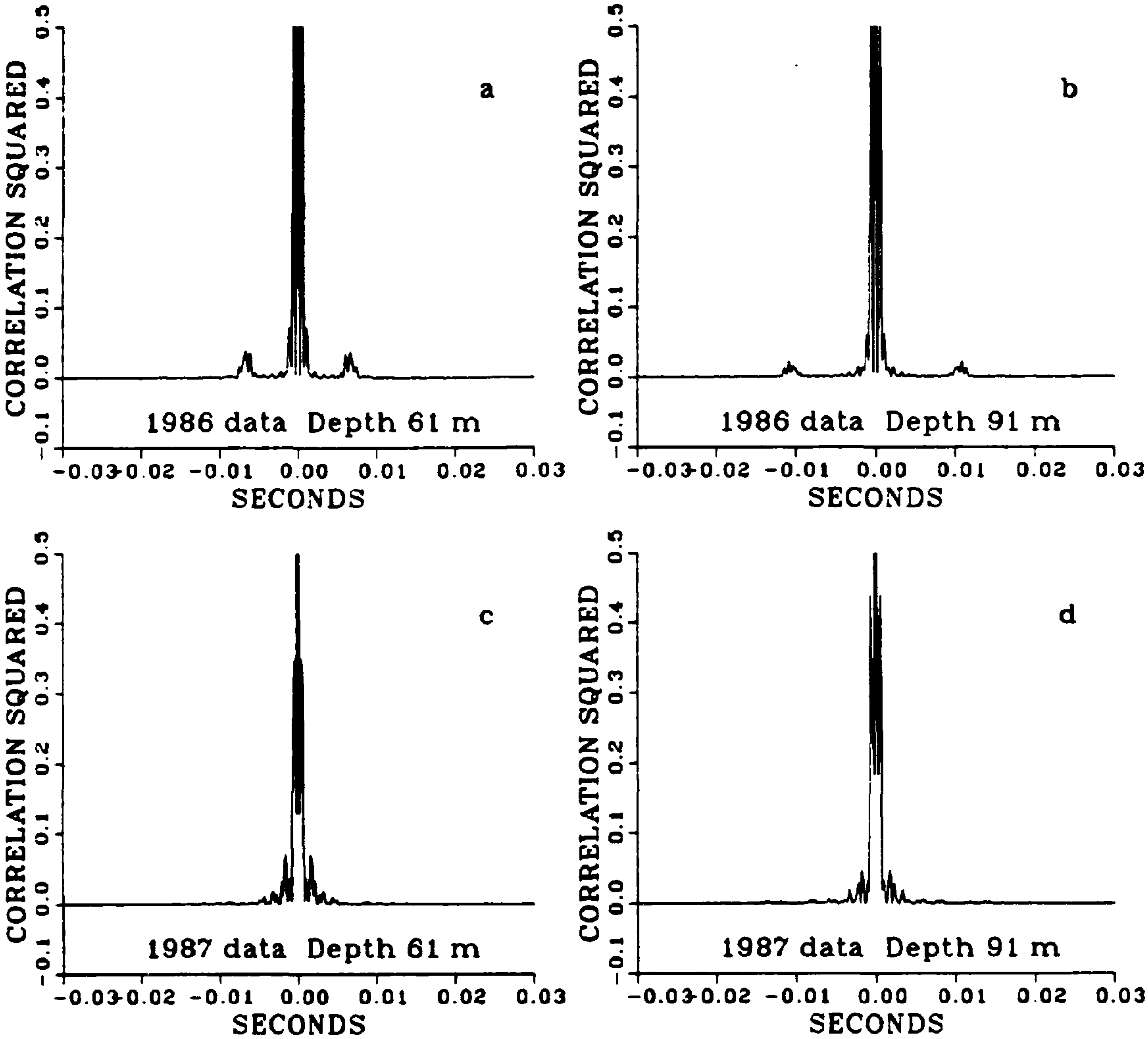


Figure 5. Average autocorrelation values squared.

but the width of the second arrival in Figure 3b, 1987 data, was too large to allow the program to select and divide the direct and reflected arrivals correctly. In another method tested, the normalized autocorrelation of the signal was squared, resulting in only positive values. Then the 16 data channels for a given ping were averaged, omitting any channels in which the hydrophone obviously did not function correctly. In Figure 5 this average squared autocorrelation is shown for four different examples. Figure 5a came from the data shown in Figure 1. These plots look cleaner than the deconvolutions, but the second arrival is clearly seen only in examples a and b. The envelope of the autocorrelation of the data in Figure 1 averaged with autocorrelation envelopes of data from the same pulse on other channels is shown in Figure 6a. The envelope was derived using a Hilbert transform. The Hilbert transform [4], H, of a

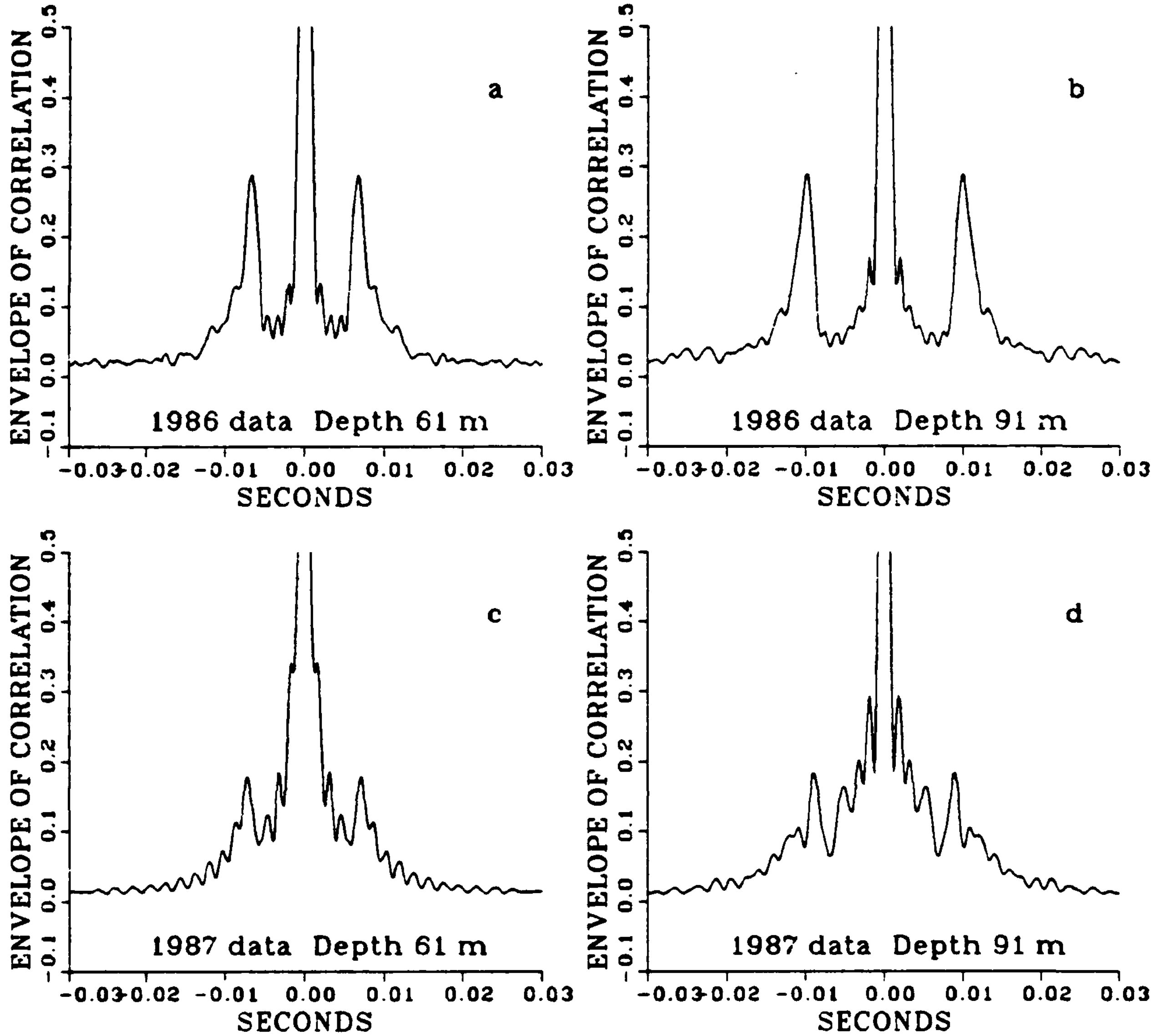


Figure 6. Average envelope of autocorrelation obtained using the Hilbert transform.

real valued time domain signal x(t) may be defined as a $\pi/2$ phase shift system or the imaginary part of the analytic signal $z(t) = x(t) + jH[x(t)]$. $H[x(t)]$ is derived from x(t) by convolution with $(-\pi t)^{-1}$. The analytic signal is obtained by suppressing the negative frequency terms and doubling the result[5]. The envelope signal E(t) of x(t) is obtained using the following equation.

$$E(t) = \{x^2(t) + (H[x(t)])^2\}^{1/2}$$

All four examples in Figure 6 indicate two arrivals and the offset between their arrival times. This formula brings out weaker arrivals and smooths the sidelobes of the autocorrelation function. The average

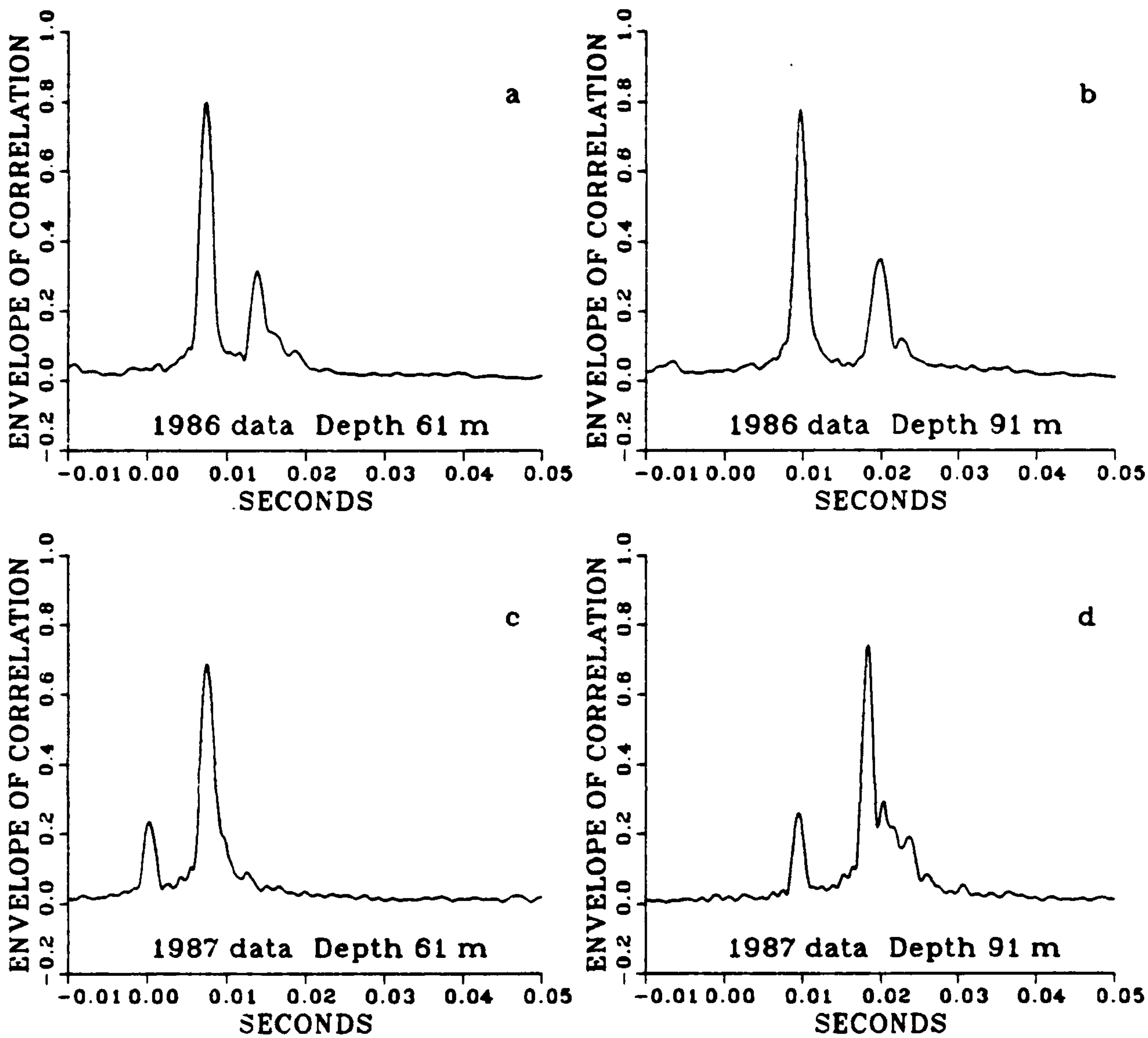


Figure 7. Average envelope obtained using a Hilbert transform of cross correlation between total signal and source pulse.

envelope, again from the Hilbert transform, of cross correlation between the same hydrophone signals used in Figure 6 and a source pulse sample is shown in Figure 7. This improves the results by distinguishing between the direct and reflected arrivals and showing the initial offset of the sampled signal. The time at which the correlation envelope is a minimum between the two main peaks will consistently be the correct cutoff time. Tests have shown that any time between the two peaks, and for which the amplitude of the envelope is far below the maximum of either peak, will give nearly identical results. Overlapping FM pulses, with 800 Hz bandwidths, arriving as little as 0.0014 seconds apart can be separated using this method. Different sound speed profiles in 1986 and 1987

caused the direct arrival to be dominant in the 1986 examples and the reflected arrival to dominate the 1987 examples.

Envelope of Correlation Algorithm

The Fortran algorithm used for calculating the correlation and applying the Hilbert transform to obtain its envelope follows. Creating a computer algorithm that makes an equation work on available equipment is an important part of the solution to any processing problem involving real digital data. This subroutine has been streamlined to save time and memory by calculating only correlation values around zero.

```
      SUBROUTINE ACOR(NA,NB,B,A)
C
C     USES NORMALIZED CONVOLUTION TO CALCULATE CORRELATION (AN)
C      AND A HILBERT TRANSFORM TO CALCULATE THE ENVELOPE (E).
C      GAINS SPEED IN THE CONVOLUTION BY ONLY CALCULATING 256
C      POINTS ON EITHER SIDE OF TIME ZERO.
C     NA = NUMBER OF POINTS IN ARRAY A
C     NB = NUMBER OF POINTS IN ARRAY B
C     A  = REAL SIGNAL DATA ARRAY
C     B  = REAL SOURCE DATA ARRAY
C     SAV  = SUM OF ENVELOPE VALUES FOR ALL PHONES USED
C
      DIMENSION A(2048),B(2048),R(4097)
      COMMON/CRDT/E(512),SAV(512)
      DIMENSION Y(512),X(512),ZR(512),ZI(512),HXI(512)
      DIMENSION AN(513)
      SA=0.
      SB=0.
      DO 70 K=1,NA
       SA = A(K) * A(K) + SA
       SB = B(K) * B(K) + SB
 70   CONTINUE
      FN = SQRT(SA*SB)
      NL = NA+257
      NF = NA-255
      DO 80 I=NF,NL
       J=I-NF+1
       R(I)=0.
```

```
      AN(J)=0.
      DO 78 K=1,NA
       NT = K + NA + 1 - I
       IF((NT).GT.NB) GO TO 78
       IF((NT).LE.0) GO TO 78
       R(I)=A(K)*B(NT)+R(I)
 78   CONTINUE
      AN(J) = R(I)/SQRT(SA*SB)
 80   CONTINUE

C     CALCULATE ENVELOPE USING HILBERT TRANSFORM

      DO 90 JN=1,512
C     CORRELATION TIME SERIES GOES INTO REAL ARRAY
        X(JN)=AN(JN)
C     PHASE VALUES SET TO ZERO IN IMAGINARY ARRAY
        Y(JN)=0
 90   CONTINUE
C     TIME TO FREQUENCY FFT
       CALL FFT842(0,512,X,Y)
      DO 92 JN = 1,512
C     FREQUENCIES GREATER THAN 0
        ZR(JN)=2*X(JN)
        ZI(JN)=2*Y(JN)
C     FREQUENCIES LESS THAN 0
      IF(JN.GT.256) THEN
        ZR(JN)=0.0
        ZI(JN)=0.0
      ENDIF
 92   CONTINUE
C     INVERSE FFT
       CALL FFT842(1,512,ZR,ZI)
      DO 100 JN=1,512
C     ENVELOPE CALCULATION
       E(JN) = SQRT(AN(JN)**2+ZI(JN)**2)
C     SUM ENVELOPE VALUES FOR AVERAGING
       SAV(JN) =SAV(JN) + E(JN)
 100  CONTINUE
      RETURN
      END
```

CONCLUSION

The average envelope of correlation between signal and source pulse samples, as shown in Figure 7, was chosen as the best aid in selecting cut-off times for removing the direct arrival from total hydrophone signals by deconvolution and reconvolution with a source pulse. Figure 7a shows the first peak centered around .008 seconds and the second peak around .014 seconds. Taking the width of the peak into account makes .009 to .013 seconds an appropriate range for the cutoff time.

In Figure 8, as an example of the use of reconvolved data, the correlation of the isolated reflection or forward scattered arrival is compared with the correlations of the corresponding total hydrophone signal and deconvolved direct arrival. Figure 8 uses the 1986 data shown in Figure 1 where the source was 61 m deep. The points are separation versus the maxima of the cross-correlation coefficient functions[6] for data from each pair of hydrophones representing a range of separations from 0 to 16 m. The line indicates a linear fit to these points. A comprehensive report on spatial coherence results from these experiments will be published separately.

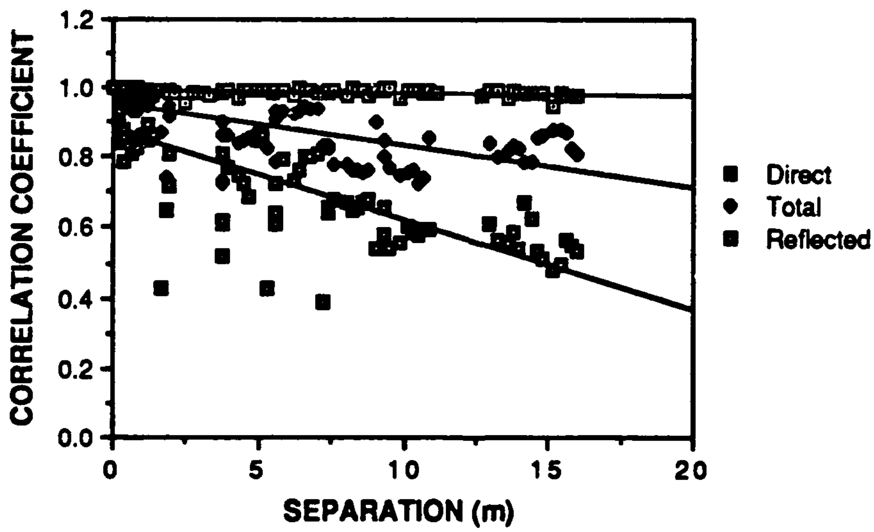


Figure 8. Cross channel correlations of direct signal, reflected signal, and total received signal are shown versus hydrophone separation for 1986 data at 915 m range and 61 m source depth.

Software developed to show the cutoff time also makes it possible to obtain relative coherent amplitudes of the direct and reflected arrivals. This information is used to study the effects of ice reflection on high frequency acoustic propagation[7].

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